Technology Development for Hydrogen Propellant Storage and Transfer at the Kennedy Space Center (KSC)

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Technology Development for Hydrogen Propellant Storage and Transfer at the Kennedy Space Center (KSC)

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NASA, Kennedy Space Center

- **We have over 50 years of Liquid Hydrogen operations experience.**

- **We have developed numerous technologies to enhance the safety of operations and equipment.**

  – Flame Detectors

  – Leak Detection

- **Recently we have made several notable advancements in these areas and in the protection of large LH2 storage vessels.**

- **We are also working on technologies for recovering water from the lunar poles and converting to H2 and O2 for propellants.**
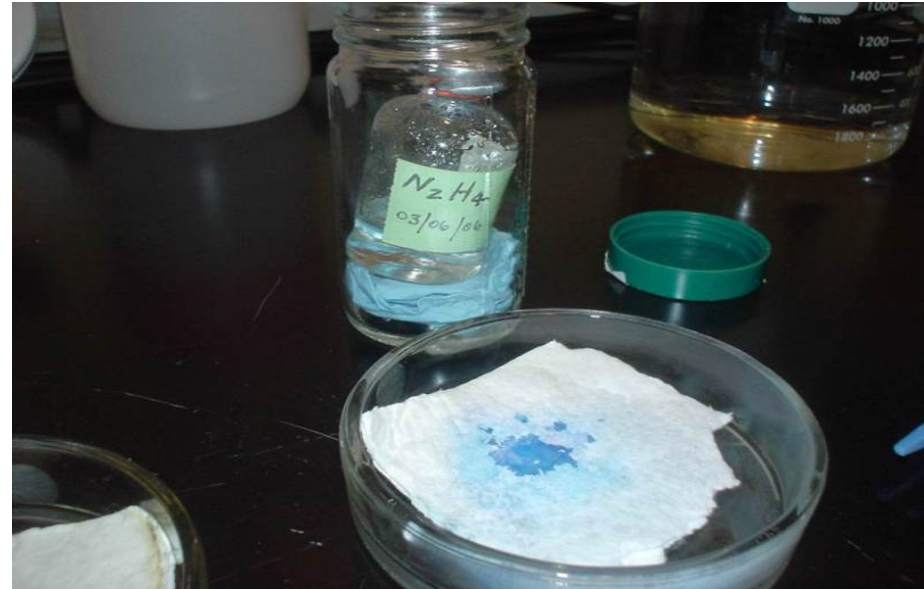
Color changing materials for hypergolic propellants

We have extensive experience with color changing chemistry for hypergolic propellants.

Hydrazine flow line with color changing sensor located under the transparent overwrap.
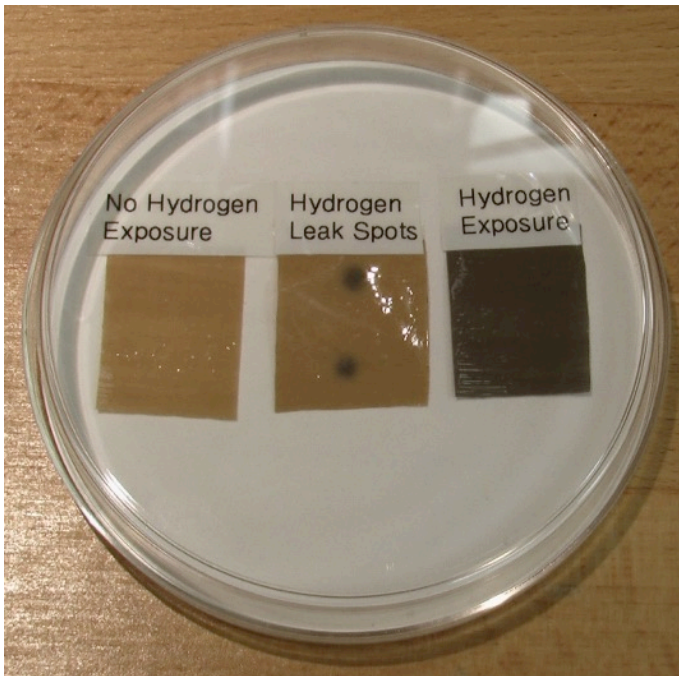

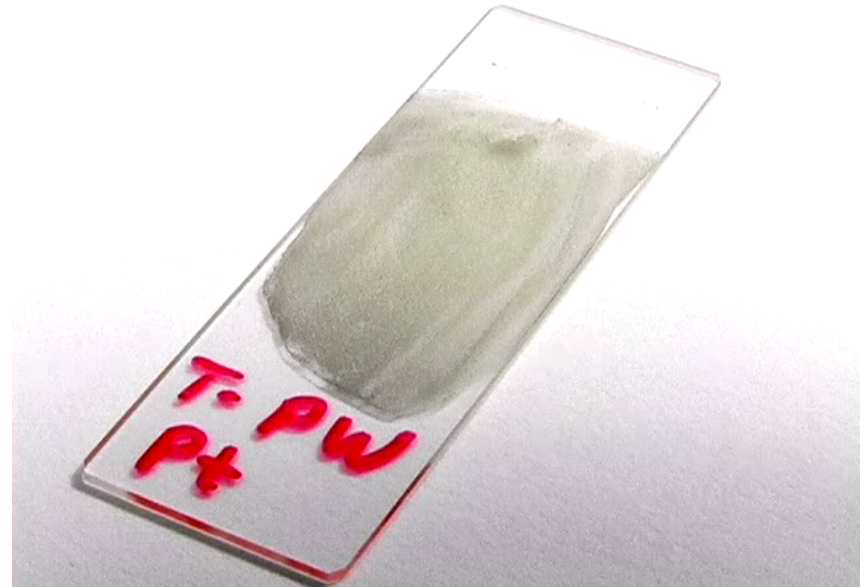Hypergolic wipes that change color when exposed to hydrazines.

Color changing hydrogen materials

We worked with the University of Central Florida to develop color changing H2 chemistry
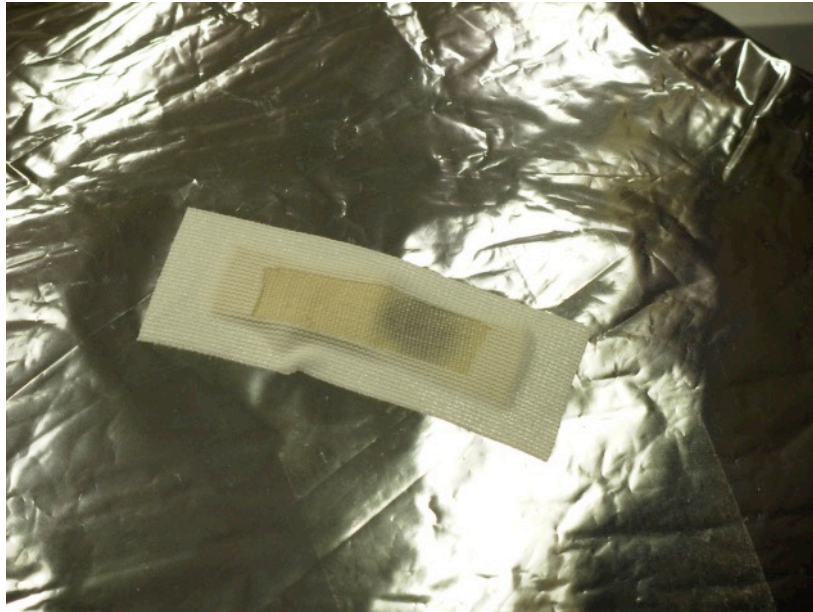

Compounds exist that change color when exposed to hydrogen. This one shows a permanent change.

This is a reversible version of a color changing compound being exposed to hydrogen.

Environmental testing of varied products

KSC Beach-side Corrosion Test Facility allowed for salt spray and (manual) acidic deposition typical of solid rocket motor effluents

In collaboration with FSEC/UCF
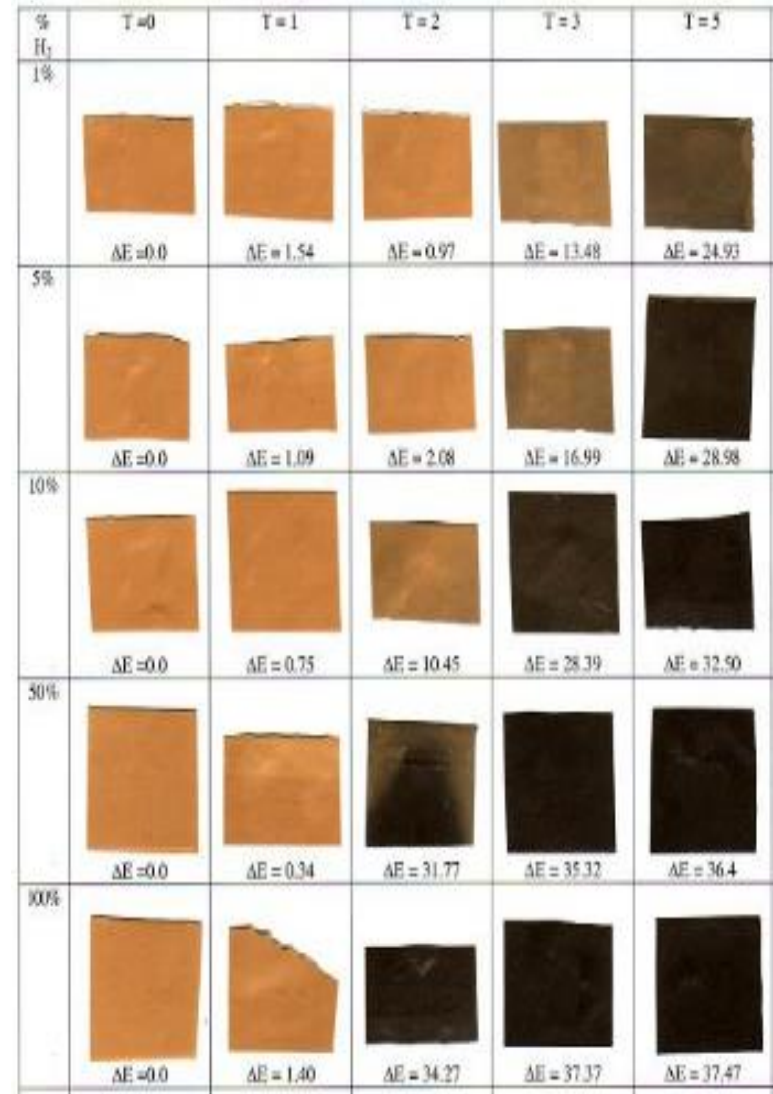
Irreversible Sensor

A patented irreversible color changing H_2 gas sensor was developed at KSC in partnership with UCF.

Changes color from a light tan to black in the presence of H_2.

Can be manufactured into any polymer part, tape, fiber, or fabric material for unlimited potential uses (extrusions with aerogel).

- Paint, Gloves, Coveralls, PPE

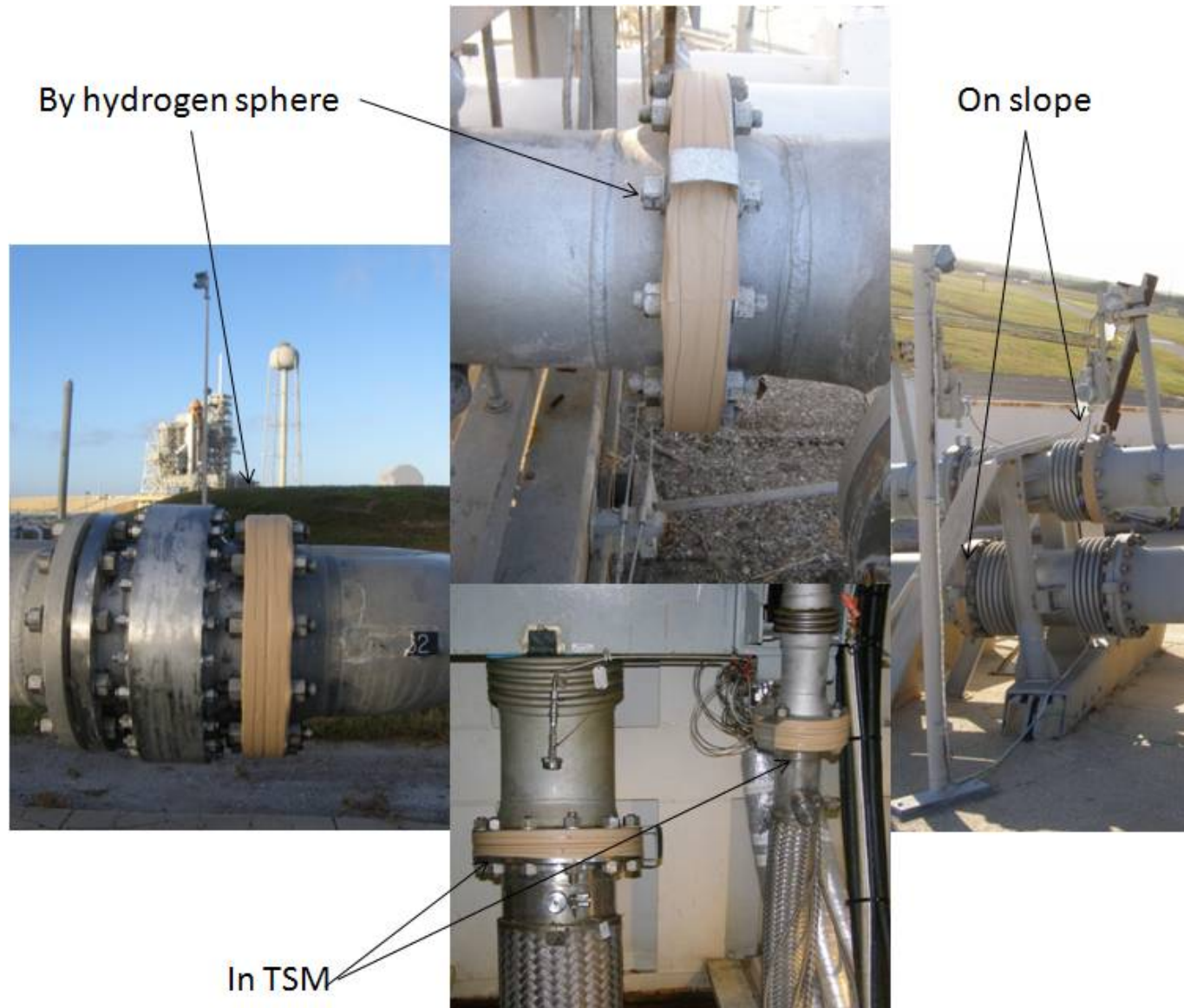Operates under ambient and cryogenic temperatures.

% H_2	T = 0	T = 1	T = 2	T = 3	T = 5
1%	ΔE = 0.0	ΔE = 1.54	ΔE = 0.97	ΔE = 13.48	ΔE = 24.93
5%	ΔE = 0.0	ΔE = 1.09	ΔE = 2.08	ΔE = 16.99	ΔE = 28.98
10%	ΔE = 0.0	ΔE = 0.75	ΔE = 10.45	ΔE = 28.39	ΔE = 32.50
50%	ΔE = 0.0	ΔE = 0.34	ΔE = 31.77	ΔE = 35.32	ΔE = 36.4
100%	ΔE = 0.0	ΔE = 1.40	ΔE = 34.27	ΔE = 37.37	ΔE = 37.47

Launch Pad Testing

**Cross Country Lines and OMBUU
Deployment for five Shuttle launches**
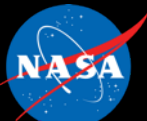
By hydrogen sphere

On slope

In TSM

https://www.nasa.gov/content/innovative-hydrogen-leak-detection-tape-earns-prestigious-award
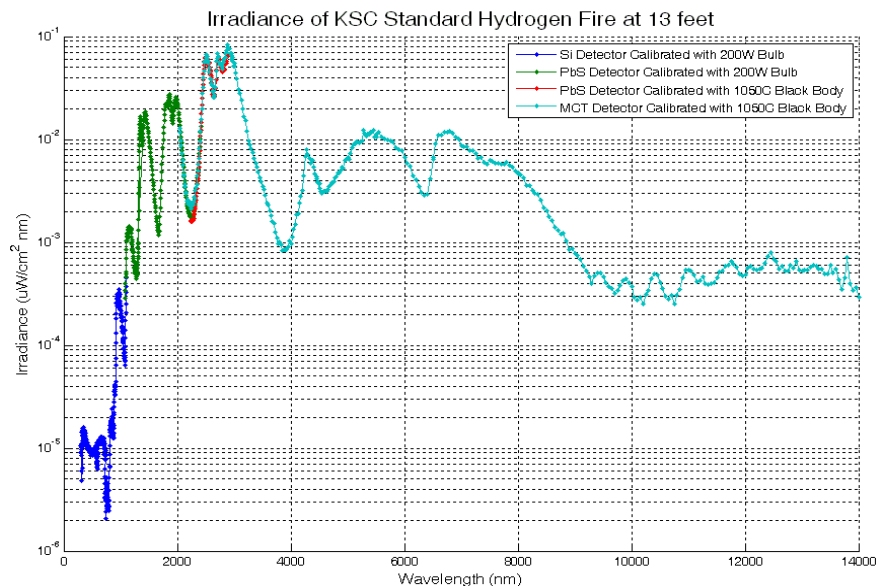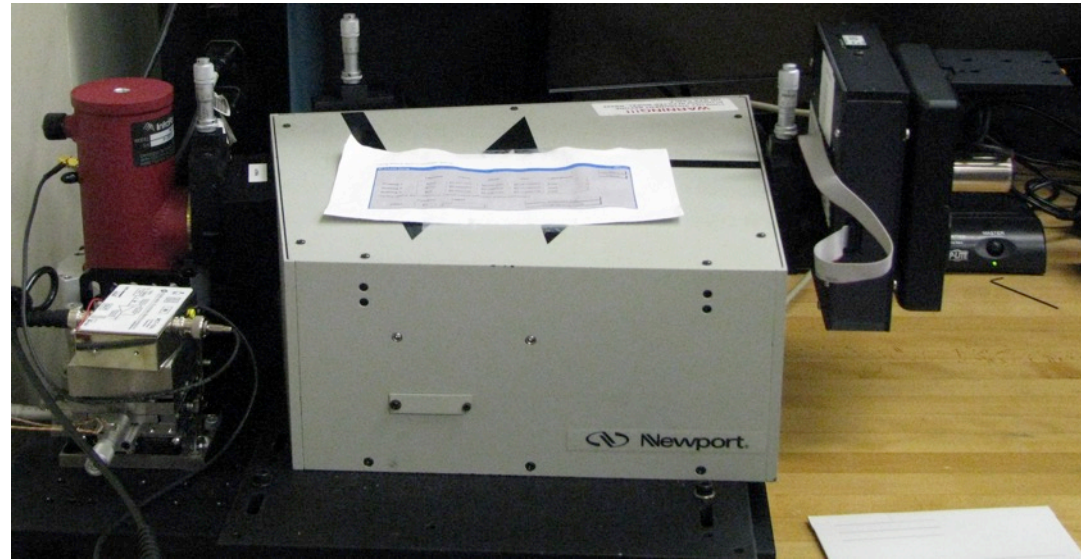
Four primary goals of this work:

1. Obtain NIST traceable spectra of a KSC standard hydrogen flame in air from the UV through the far–infrared
2. Develop a lab prototype ultraviolet hydrogen flame simulator
3. Determine if IR absorption can be used to quantify water content in the Resolve surge tank.
4. Determine the impact of atmospheric water vapor infrared absorption on the operation of the new IR hydrogen fire detectors.

Hydrogen Fire Spectroscopy

We started the project having taken the spectra of a standard KSC hydrogen flame through the visible, near-IR, and far-IR radiation bands.


A far-IR configured spectrometer.

Irradiance of KSC Standard Hydrogen Fire at 13 feet

- Si Detector Calibrated with 200W Bulb
- PbS Detector Calibrated with 200W Bulb
- PbS Detector Calibrated with 1050C Black Body
- MCT Detector Calibrated with 1050C Black Body

Our irradiance data at project start.

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Hydrogen Fire Spectroscopy

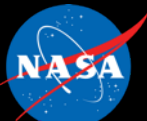We purchased a UV sensitive photomultiplier tube and a NIST traceable UV Emitting Source (a Deuterium Bulb).

We coordinated the use of the UV bulb with safety.
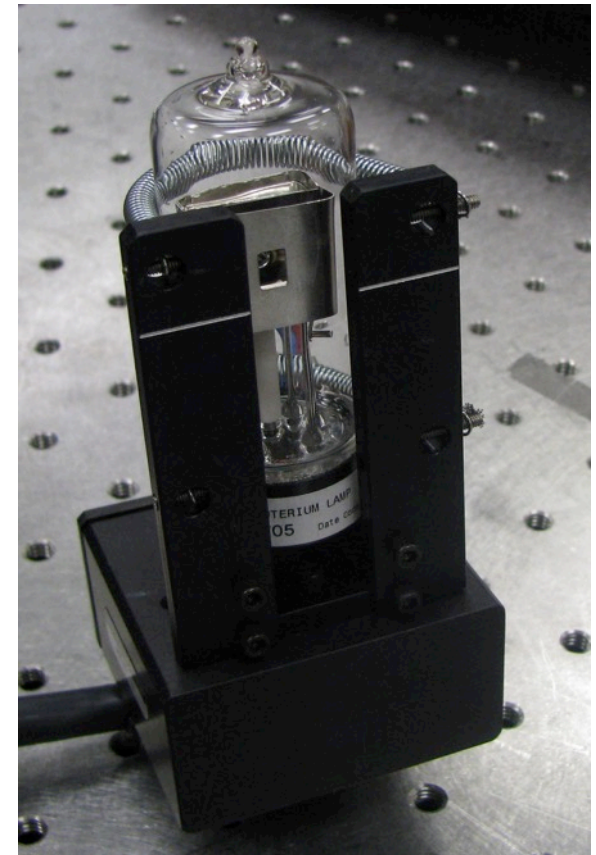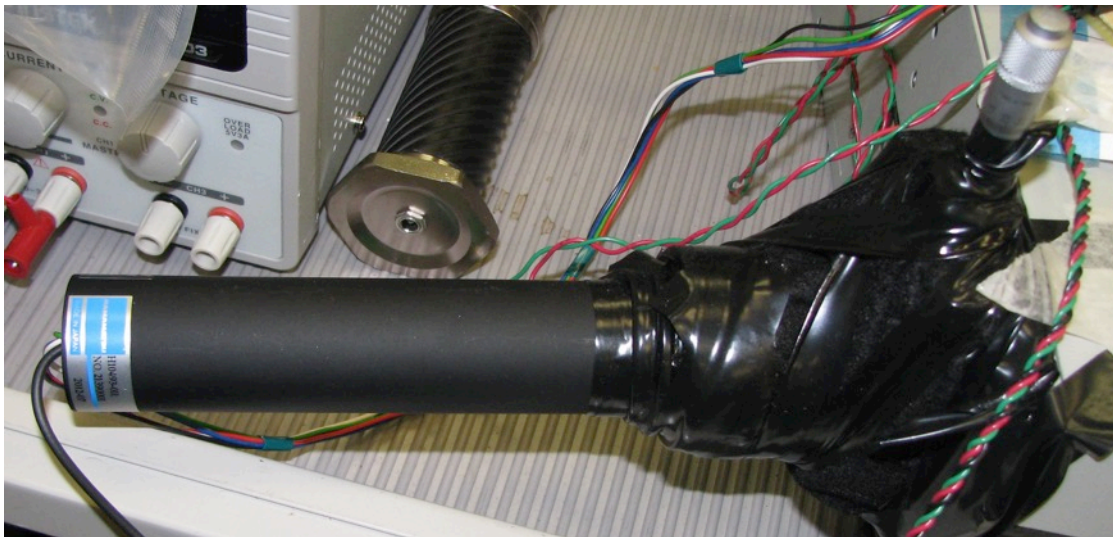
Deuterium Bulb
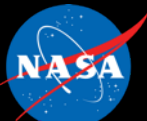

Photomultiplier Tube

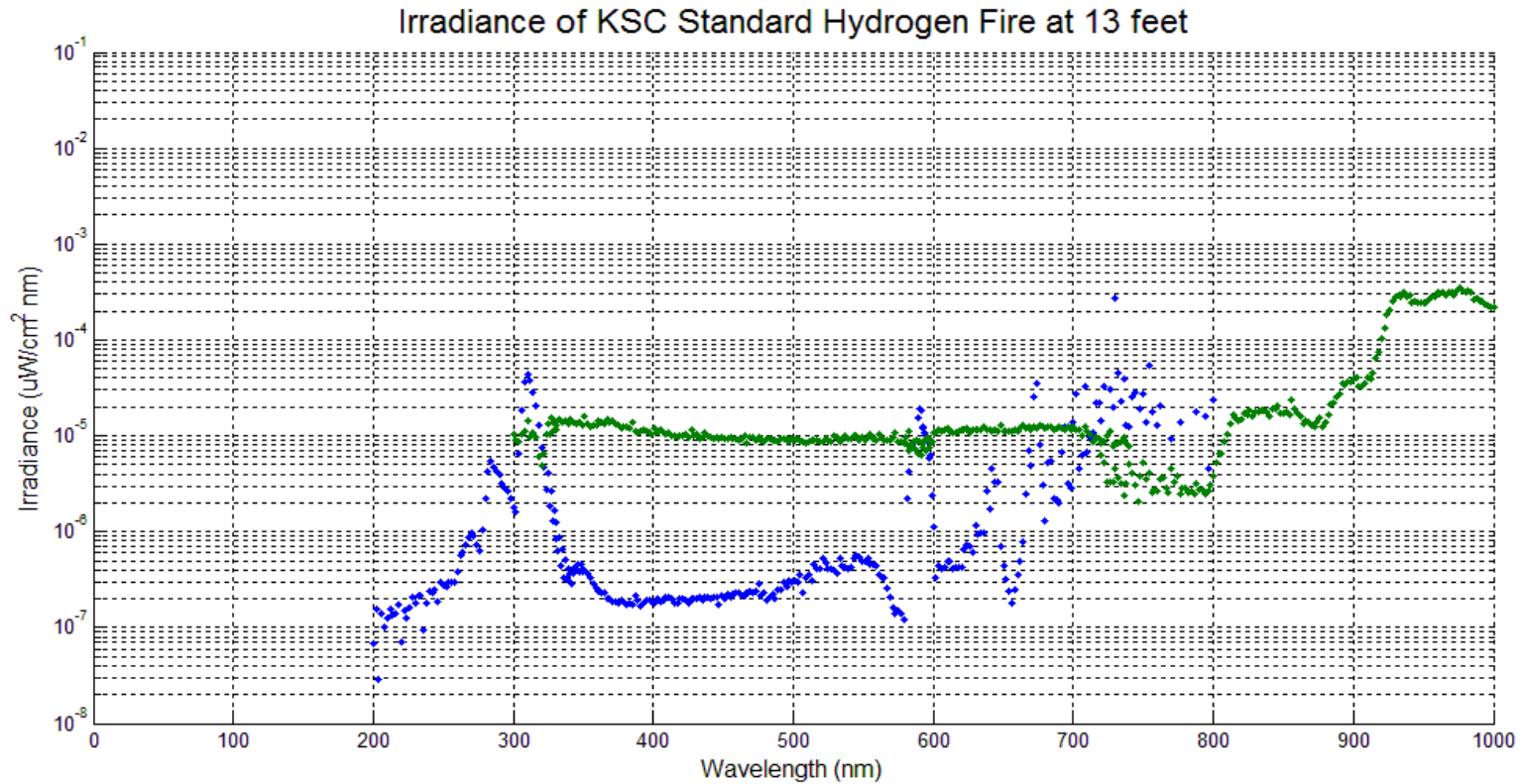# Hydrogen Fire Spectroscopy

Fire

All fire measurements were performed at night at the fire training site. All safety procedures were approved and followed.

Hydrogen Fire Spectroscopy

Irradiance of KSC Standard Hydrogen Fire at 13 feet
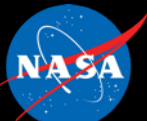
Great Results. The green curve is our prior visible range silicon detector results. The blue curve shows the new data using the photomultiplier tube configuration with the UV bulb calibration. Note the peaks in the 300 nm region.

Hydrogen Fire Spectroscopy
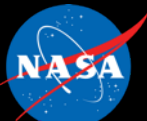
Back in the 1990's we developed, patented, and fielded to Shuttle Ground Operations a ultraviolet hydrogen flame simulator. This device is still in use, but uses high voltage bulbs, an external battery pack, and an outdated processor.

Hydrogen Fire Spectroscopy

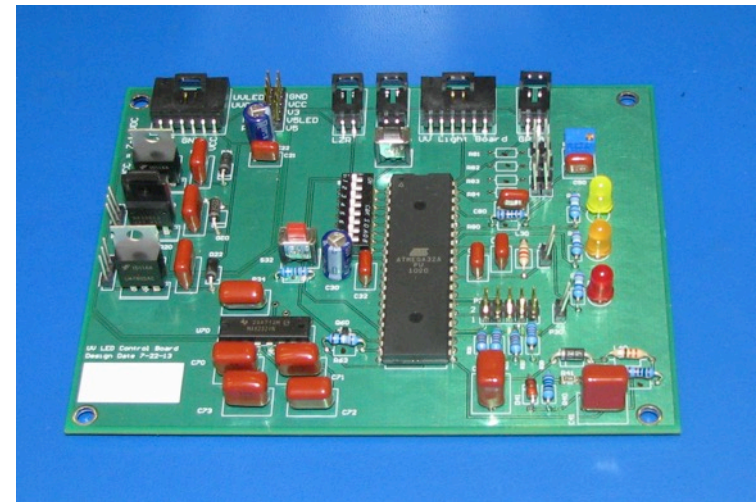We've shown that UV LEDs can be used to build a hydrogen fire simulator.

We've designed and built a control board for the UV simulator.

The goal is to have a prototype unit by the end of the CTC project.

We've coordinated with Ground Operations and they want to continue this work and convert the prototype to a field unit during the second half of the year.

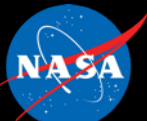| Nominal Wave	Serial Number	Peak Wave
240	O13	242.2
240	O14	242.2
240	O15	242.2
240	O18	242.2
265	W47	268.8
265	X46	268.8
280	H64	288.3
280	H65	288.3
255	A6	261.3
255	A7	260.8

UV emitting LEDs

LED control board

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Hydrogen Fire Spectroscopy

Working with the Resolve team, we measured the IR transmission through a small test surge tank to see if desired concentrations of water vapor could be measured in this fashion.
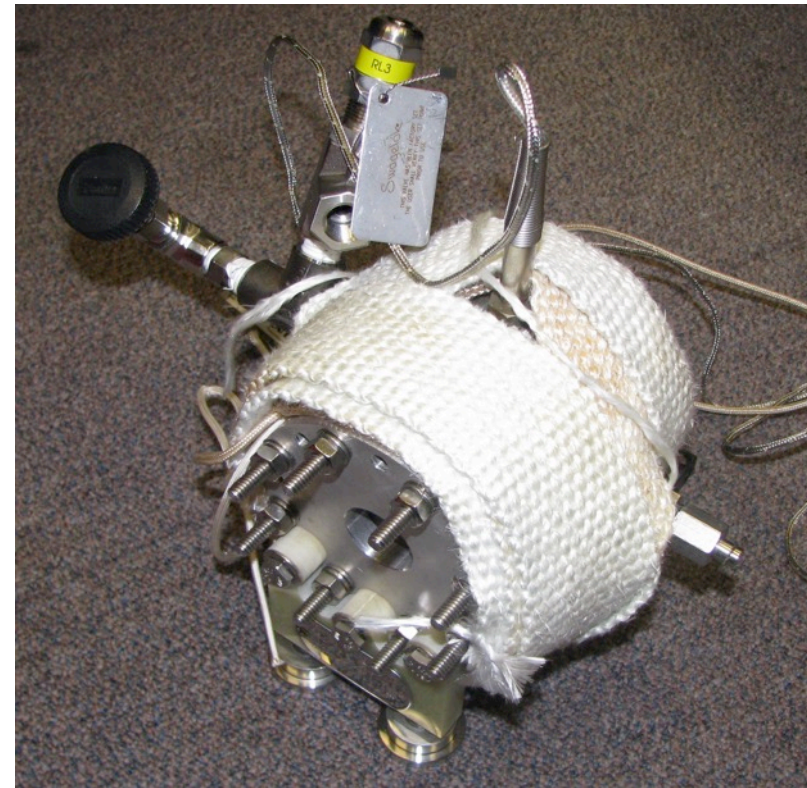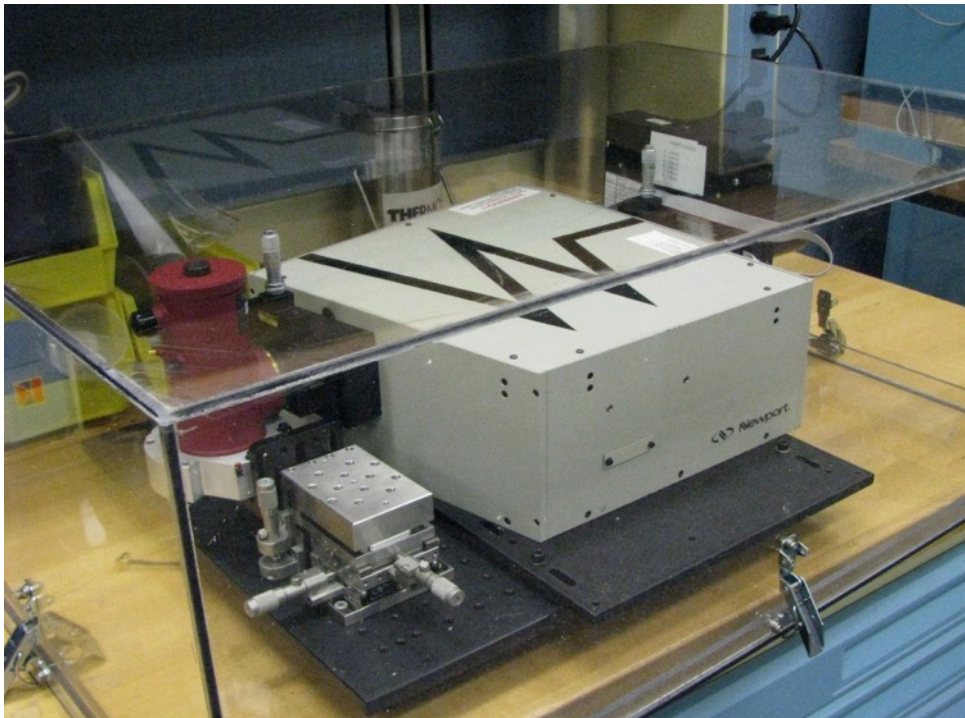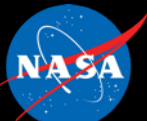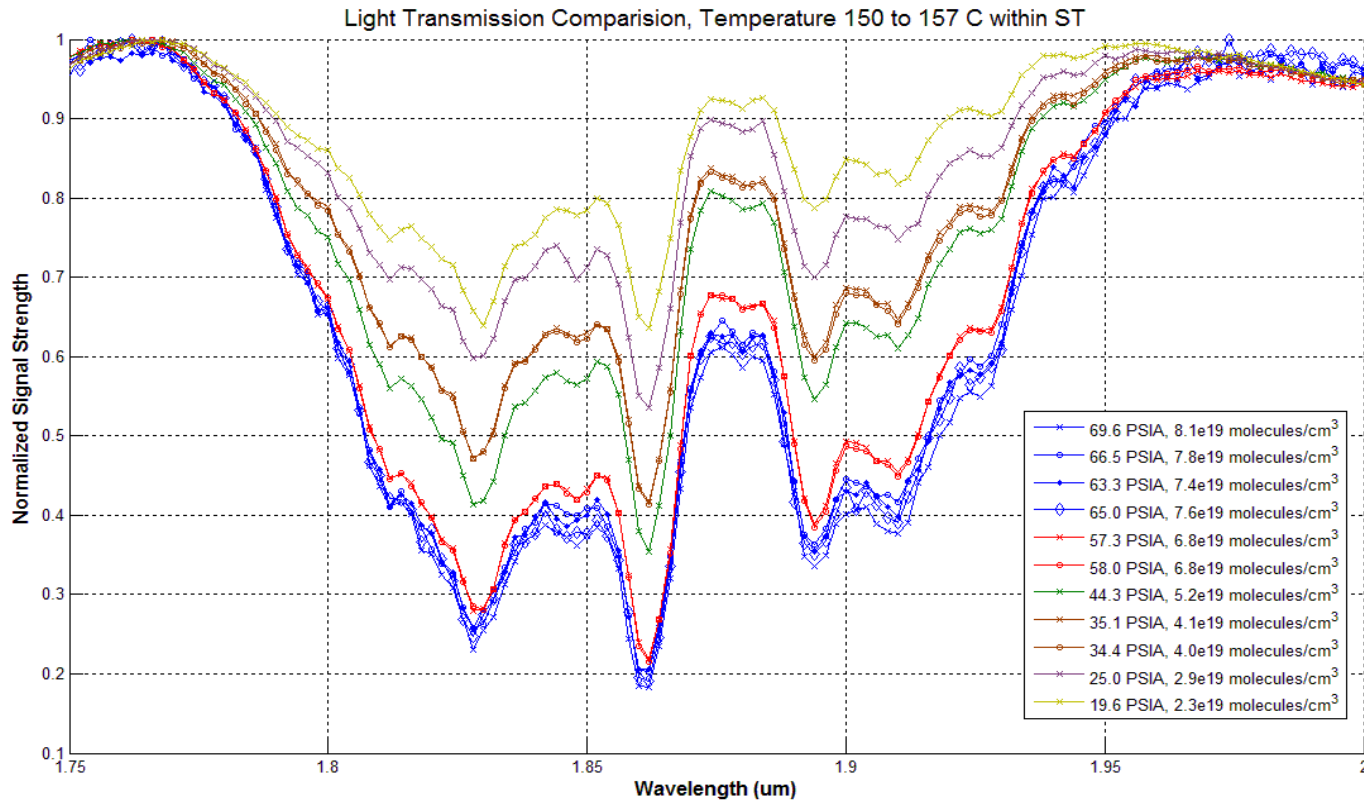

Surge Test Tank

Spectrometer located in a purged housing to minimize absorption by water in the atmosphere.

Hydrogen Fire Spectroscopy

Light Transmission Comparision, Temperature 150 to 157 C within ST

Legend:
- 69.6 PSIA, 8.1e19 molecules/cm^3
- 66.5 PSIA, 7.8e19 molecules/cm^3
- 63.3 PSIA, 7.4e19 molecules/cm^3
- 65.0 PSIA, 7.6e19 molecules/cm^3
- 57.3 PSIA, 6.8e19 molecules/cm^3
- 58.0 PSIA, 6.8e19 molecules/cm^3
- 44.3 PSIA, 5.2e19 molecules/cm^3
- 35.1 PSIA, 4.1e19 molecules/cm^3
- 34.4 PSIA, 4.0e19 molecules/cm^3
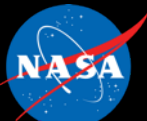- 25.0 PSIA, 2.9e19 molecules/cm^3
- 19.6 PSIA, 2.3e19 molecules/cm^3

The results were promising, indicating that this approach would work. The Resolve project is proceeding forward with the use of IR absorption as a method for the measurement of water vapor.

Hydrogen Fire Spectroscopy
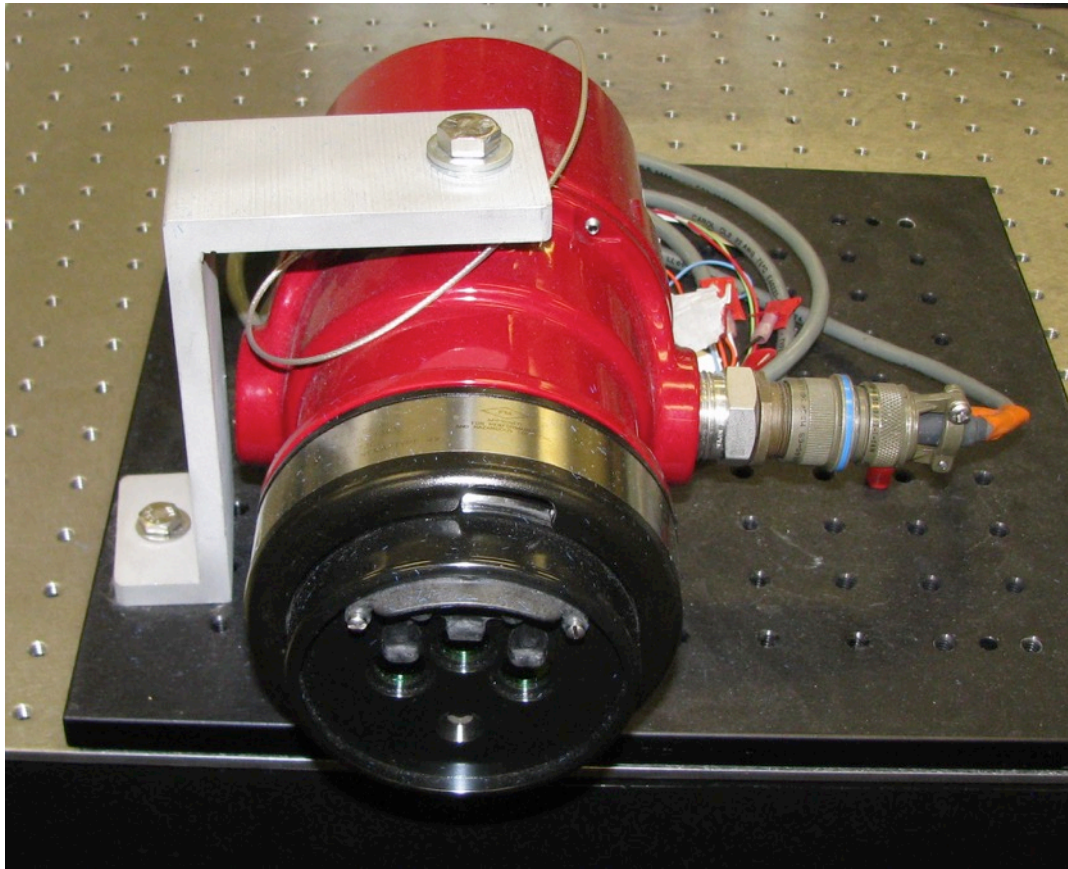
An infrared based hydrogen fire detector

We are just starting work on this last task, to determine the impact of water vapor infrared absorption on the operation of the new IR fire detectors. We hope to complete this work before the holidays.

Air Leaks in LH2 Storage Vessels

- **Large liquid hydrogen (LH2) tank are used widely in industry and are vital infrastructure for NASA**

- **LH2 tanks are double walled and can develop air leaks into the perlite filled annular region**

- **Opportunities to remove LH2 tanks from service for repairs are limited**

- **If leaks persist, large quantities of air can be ingested and frozen into the perlite's interstitial spaces**

- **What are the risks of this failure?**
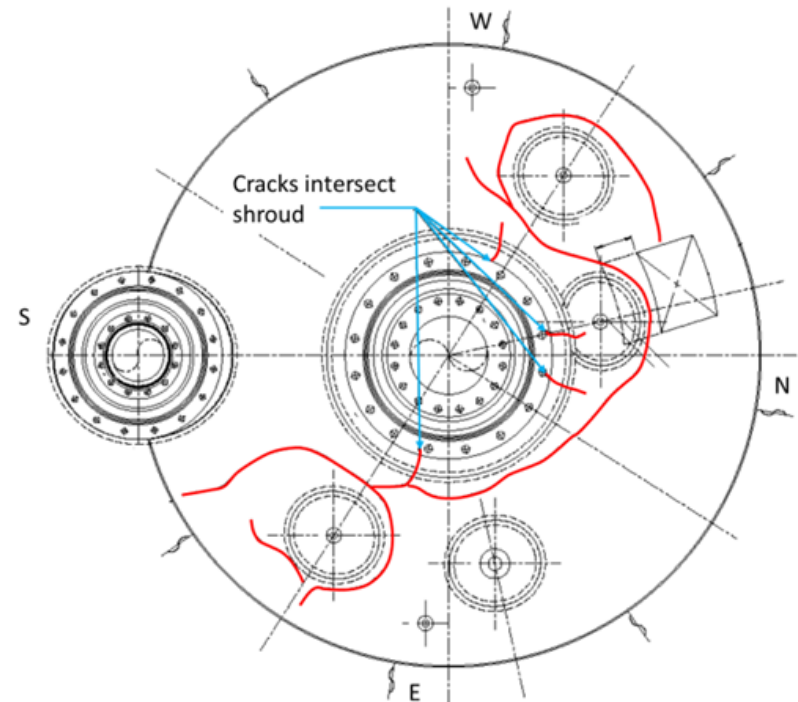
- **Stennis Space Center's LH2 tank at their B-1 test facility developed a vacuum leak into the annular region in 2011**
- **Rocket engine testing requirements resulted continued use with high boil-off rates**
- **Upon subsequent removal from service, the carbon steel outer tank wall dropped below 90 K**
- **Large cracks formed 18 days after tank drain**

Cracks intersect shroud
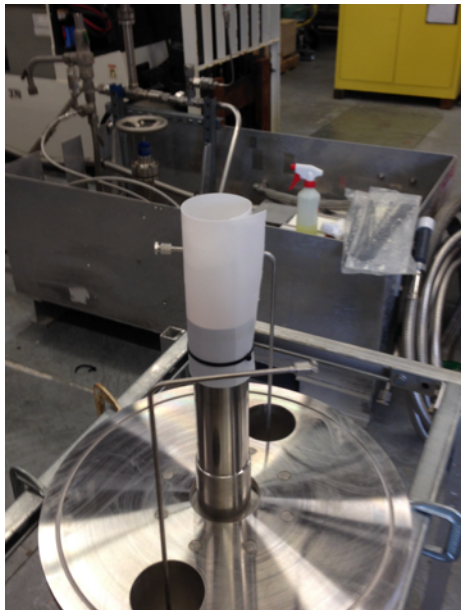
Air Leaks in LH2 Storage Vessels

- **We evaluated two potential methods to safely remove large quantities of frozen air from the annular region of an LH2 tank**
    - Annular evacuation concurrent with tank drain
    - Application of heat to the outer tank wall throughout tank drain and warm up
- **Perform testing, analysis, and develop equations to enable proper evaluation of proposed methods**
    - Experimental test to determine thermal conductivity of perlite that has air frozen into its interstitial spaces
    - Mixing model analysis to determine solid air/perlite void fractions
    - Analytical equation development
        - Air quantification and evacuation time
        - Leak rate determination
        - Tank heat leak and melting time
        - Heating power requirement determination
    - Thermal model of a specific tank case
    - Time-to failure analysis
    - Engineering analysis of a specific case (950,000 gallon tank)

- **Determine the thermal conductivity of perlite that has nitrogen frozen into the interstitial spaces**

- **Test set-up**
    - Cryomech AL230 cold head
    - 5 inches of perlite
    - 8 silicon diode temperature sensors throughout (Scientific Instruments 410AA)
    - Aerogel blanket wrap (10 ft. long, 10 mm thick)
    - Copper radiation shield (supplied with liquid nitrogen) 2 inches above perlite (upper boundary condition)
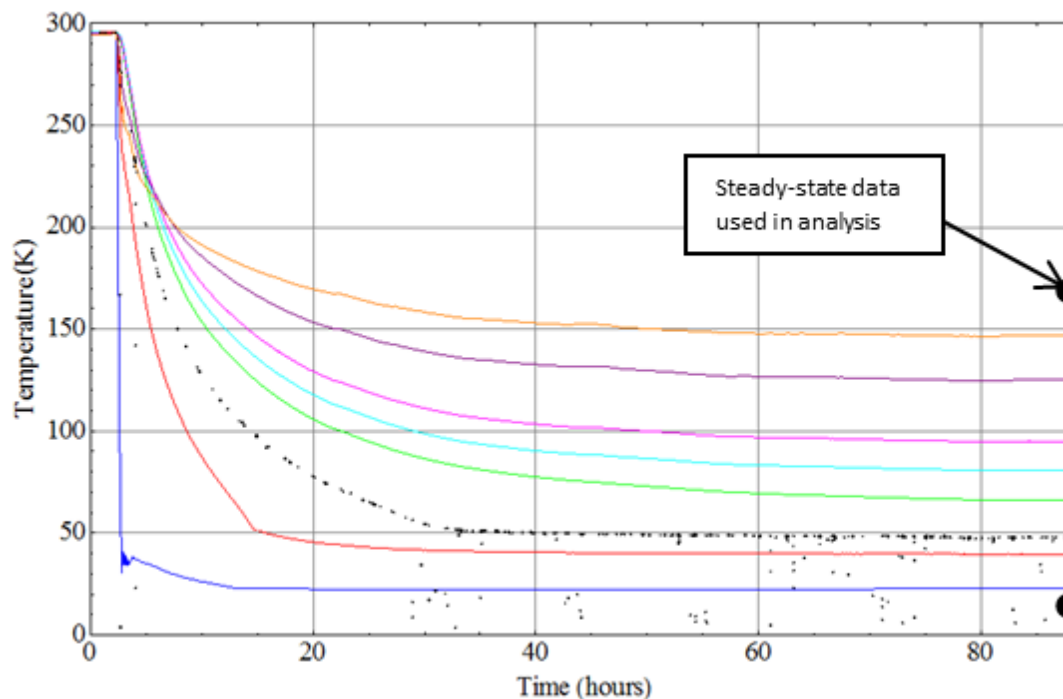   - MLI lined vacuum can covering entire set-up

Air Leaks in LH2 Storage Vessels

- **Data analysis**
  - Data suggests frozen nitrogen present at sensor locations T01, T02, and T03
    - Temperature at these locations drop below 50 K
    - Freezing point can be seen as "knees" in the curves
  - 28.9 mW/m-K (+/- 11% due to sensor location measurement limitations)


T01 through T08
(bottom to top)

Void Fraction Analysis

- **A mesoscopic numerical tool employing a Lattice Boltzmann algorithm is used to calculate the effective thermal conductivity of mixture of materials**
    - Nitrogen background gas (7.7 mW/m-K)
    - Frozen nitrogen crystals (250 mW/m-K)
    - Solid, non-porous perlite (1,300 mW/m-K - silica)
    - Mixture (28.9 mW/m-K – experimentally determined)
- **Model verified against clean perlite thermal conductivity data**
- **Mixture ratios varied until experimentally determined thermal conductivity of 28.9 mW/m-K was achieved.**
- **18.5% of the volume is predicted to be filled with solid nitrogen crystals**
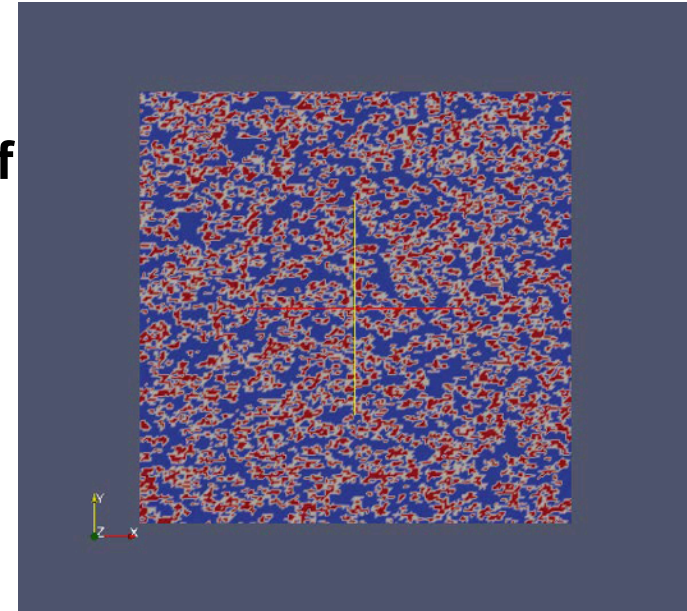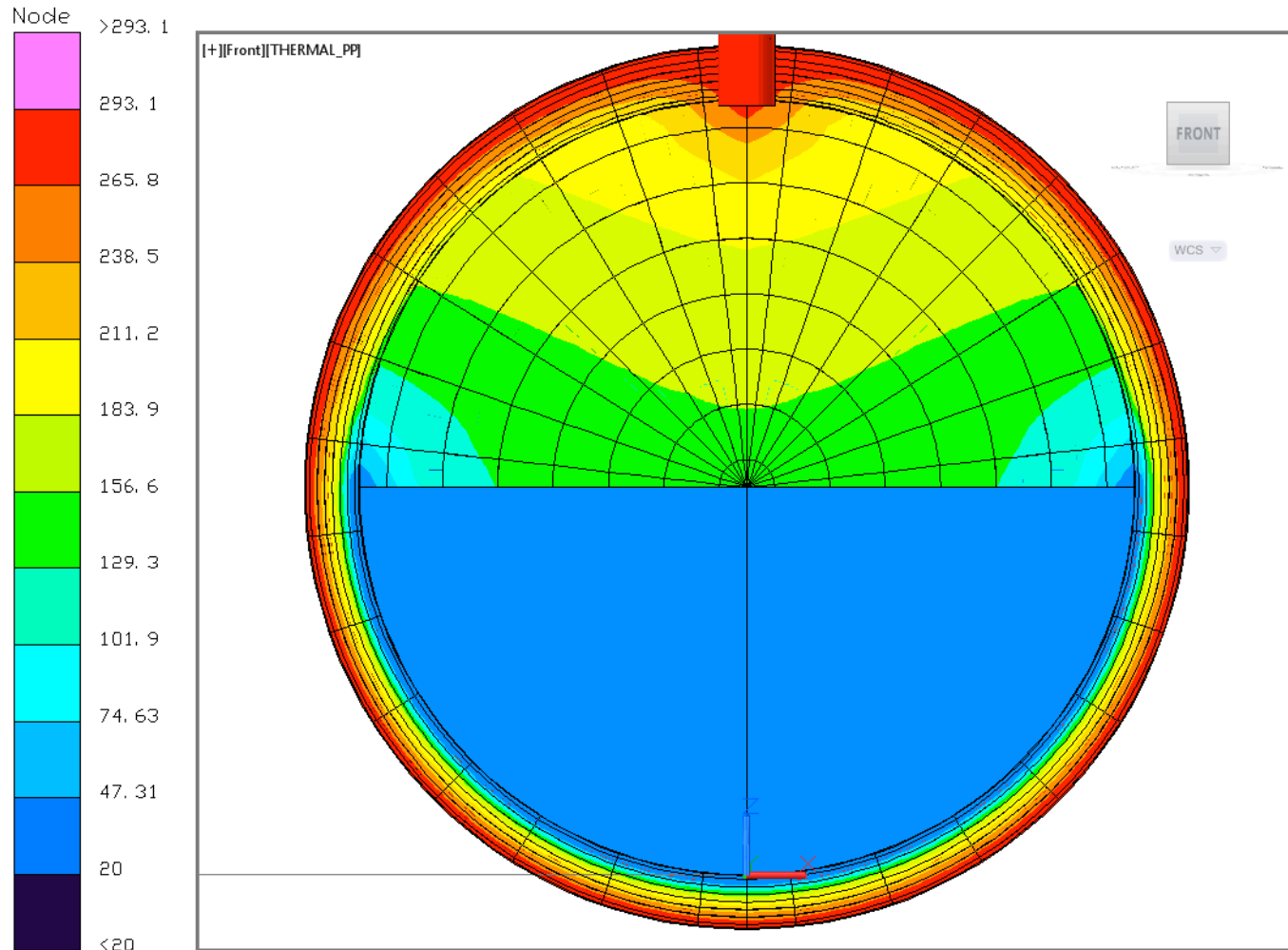

Quartet Structure Generation Set, QSGS-generated porous medium, 77% porosity perlite, 27.5% volume fraction ice.

Air Leaks in LH2 Storage Vessels
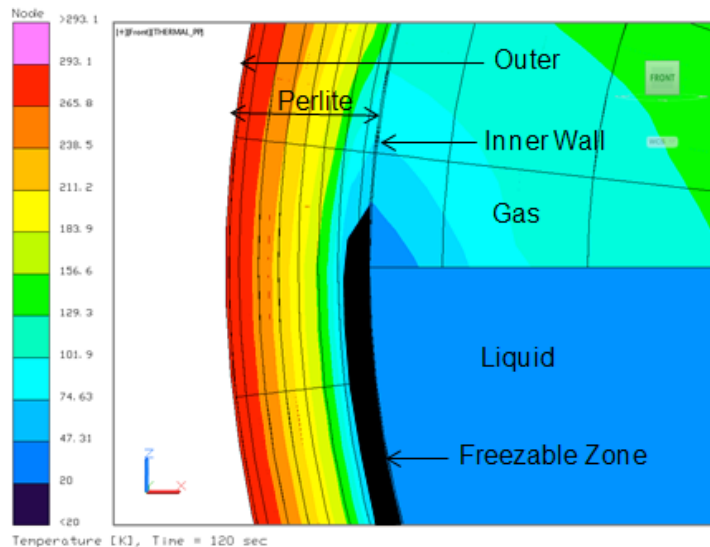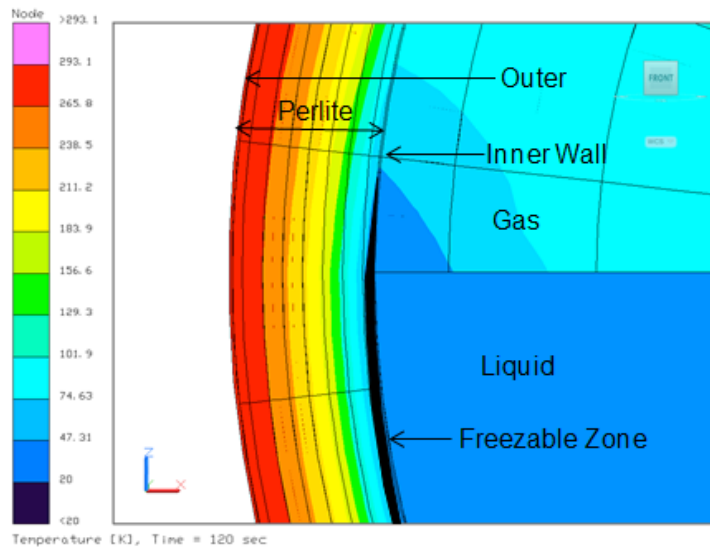
180 millitorr annular pressure

Frozen nitrogen in perlite
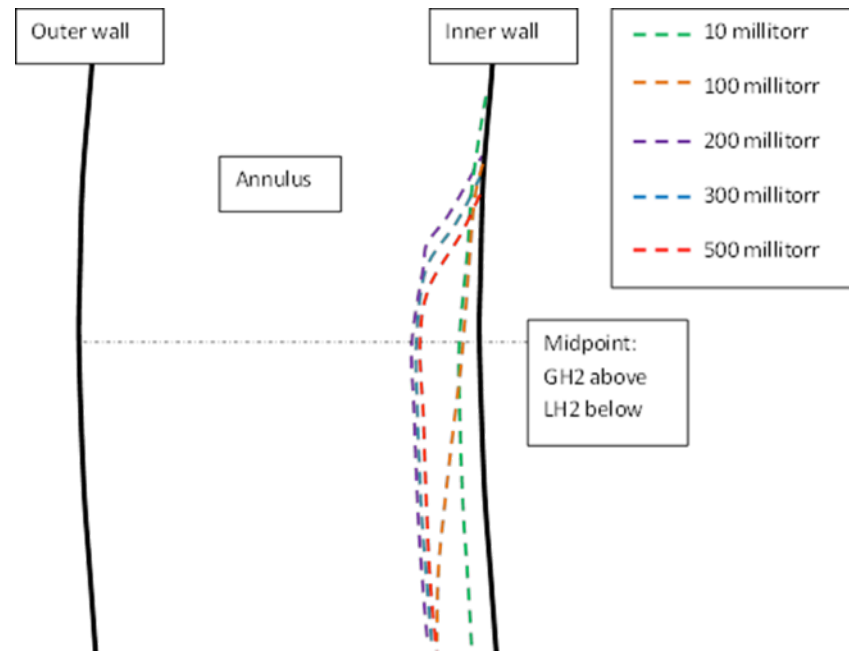

Temperature [K], Time = 120 sec

Air Leaks in LH2 Storage Vessels

Increasing thermal conductivity of residual gases and perlite/ nitrogen mixture combat each other. Maximum freezable volume is achieved between 200 – 300 microns.

Air Leaks in LH2 Storage Vessels

- A zone extending 22.6 cm (8.9 in) from the inner tank wall is cold enough to hold air in the frozen form when the annular pressure is 24 Pa (180 millitorr)
- If the storage tank is full, that results in a volume of approximately 225 m3 (7,950 ft3)
- The fraction of solid nitrogen crystals within that space is approximately 18.5%
- Therefore, up to 42 m3 (1,500 ft3) of nitrogen can be frozen in the perlite around the inner tank
- The density of solid nitrogen is 550 kg/m3, so the annular space may hold at most, 23,000 kg of solid nitrogen
- That much nitrogen, frozen from air, would result in an annular pressure rise to 31 Pa (230 millitorr) due to residual helium and neon that remain in the gaseous state
- Assuming a constant leak rate of approximately 55 sccs (calculated using equation on slide 12), it will take approximately 3.6 years to leak enough air into the tank to increase the pressure from 180 millitorr to 230 millitorr

Air Leaks in LH2 Storage Vessels

- **The time-to-failure can be extended significantly by periodically evacuating the annular space to maintain a pressure near 2.7 Pa (20 millitorr)**

- **In this case, the freezable zone increases to 626 m3, equating to a maximum of nearly 64,000 kg of frozen air**

- **It would take more than 20 years to leak in that much air at a constant rate of 55 sccs**

- **Buys time, but is not a problem solution**
  - Structural calculations required to determine the maximum additional weight that is acceptable
  - Likelihood of tank fracture upon drain increases with air ingestion
  - Good records required to ensure proper heating/evacuation calculations

Air Leaks in LH2 Storage Vessels

- **The predominant two constituents of air are nitrogen and oxygen**
  - N2 triple point: 63 K / 12.5 kPa (94,000 millitorr)
  - O2 triple point: 54 K / 0.15 kPa (1,100 millitorr)
- **Maintain the annular pressure below 133.3 Pa (1,000 millitorr) in order to prevent the frozen air from liquefying as it warms**
- **Data from the LC-39B pump down logs show an evacuation rate of 1.5 – 1.7 Pa (11-13 millitorr) per hour when pumping in the 133.3 – 60 Pa (1,000 – 450 millitorr) range: 1 mole/hour**
- **21.3 Pa (160 millitorr) needs to be removed from the annular space in order to reduce the pressure from 24 Pa (180 millitorr) back to the nominal 2.7 Pa (20 millitorr)**
- **From the ideal gas law, and the percentages of Helium and Neon in air, it is determine that 612,000 moles of air need to be removed from the annulus**
- **With continuous pumping at a rate of 1 mole per hour, it would take nearly 70 years to evacuate the air while maintaining the pressure below 133.3 Pa (1,000 millitorr)**

Air Leaks in LH2 Storage Vessels

- **Keep the temperature of the outer tank above the freezing point of water to prevent cracking**
    - Ductility limit of carbon steel is approximately 245 K
    - Freezing point of water is 273.2 K
- **Worst case heat leak into the tank at STP is 17.1 kW**
- **17.1 kW could melt 17,700 kg of air in approximately 6.7 hours**
- **The heat of vaporization of air is 201.4 kJ/kg, so it would take 3,570 MJ to vaporize the entire 17,700 kg mass of liquid air.**
- **376 MJ/hr or 104 kW (distributed over 374 m2) will be required to keep the outer wall in a safe temperature range (>275K) during the melting/vaporization process**
- **We looked at electrical heaters and while these are feasible, water spray is much easier. We recommend a water deluge type system be installed where degradation is suspected.**

Air Leaks in LH2 Storage Vessels

- **A distance 7.62 m (25 ft.) from the outer tank wall is classified as Class 1 Division 2**
- **All electronics within this zone must have sealed connections and surge protection**
- **The exposed surface of a heater may not exceed 80% of the autoignition temperature of hydrogen (773 K)**
- **Any hot surface entering that area may not exceed 618 K**
- **4 Heating methods were considered**
    - Polyimide Heaters
    - Fans
    - IR Heaters
    - Water spray

Hydrogen in Space

- **NASA is working on a technology areas called In Situ Resource Utilization, to harvest local materials in the solar system and convert them to useful products.**

- **There are very significant amounts of water on the Moon in the polar region and on Mars.**

- **The Lunar deposits could support an industry providing propellants (hydrogen and oxygen) in cis-lunar space and down to low Earth orbit; studies have shown this is economical.**

- **Multiple missions have demonstrated that the lunar polar regions contain large quantities of hydrogen, much in the form of water.**
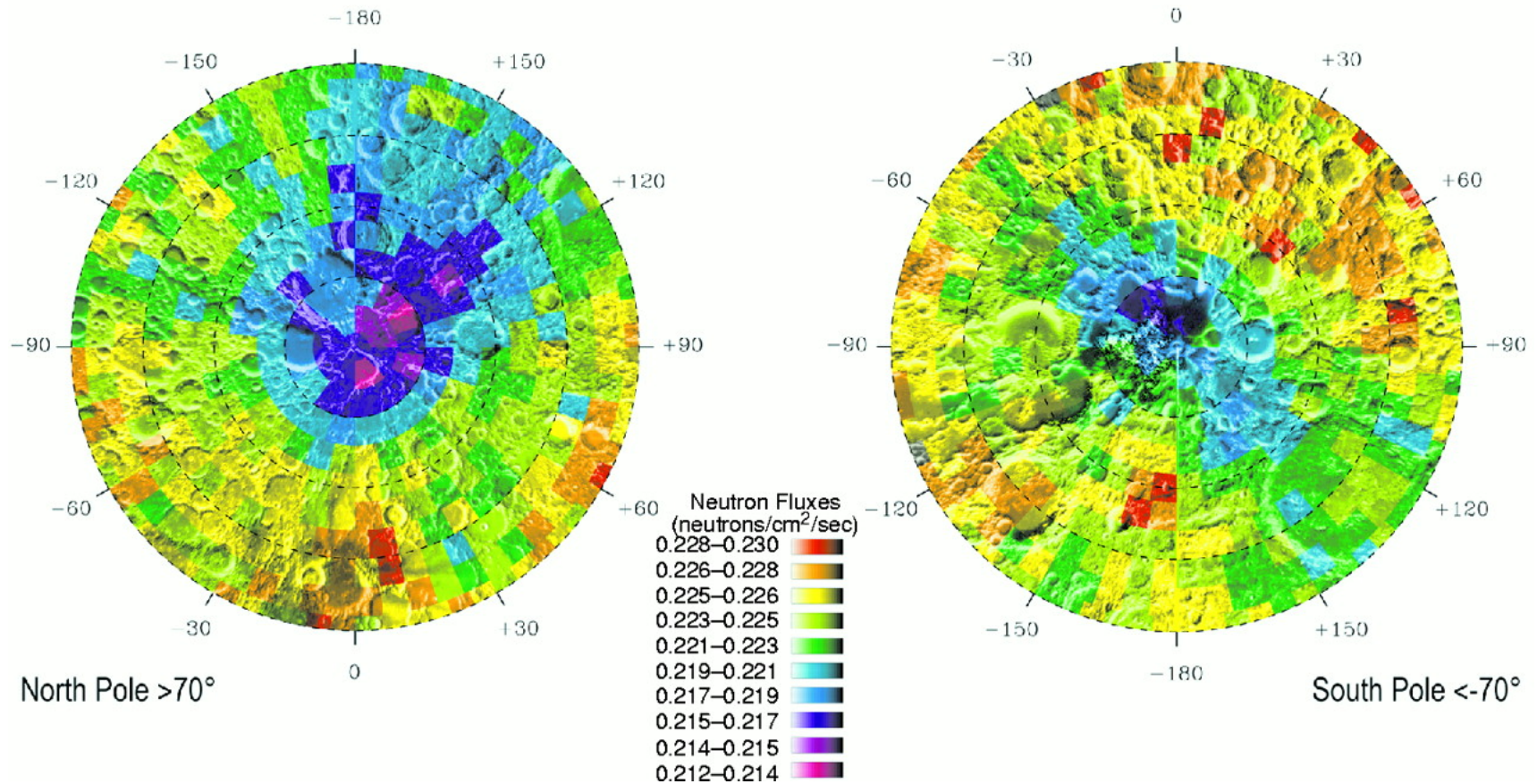

Image of the Polar Regions in Neutrons indicative of Hydrogen containing materials, Ref: Fluxes of Fast and Epithermal Neutrons from Lunar Prospector, Feldman, et. al., Science 1998.

- **The Lunar Crater Observation and Sensing Satellite (LCROSS) mission was designed to provide direct evidence (1). On 9 October 2009, a spent Centaur rocket struck the persistently shadowed region within the lunar south pole crater Cabeus, ejecting debris, dust, and vapor.**

- **Near-infrared absorbance attributed to water vapor and ice and ultraviolet emissions attributable to hydroxyl radicals.**

- **The concentration of water ice in the regolith at the LCROSS impact site is estimated to be 5.6 $\pm$ 2.9% by mass.**
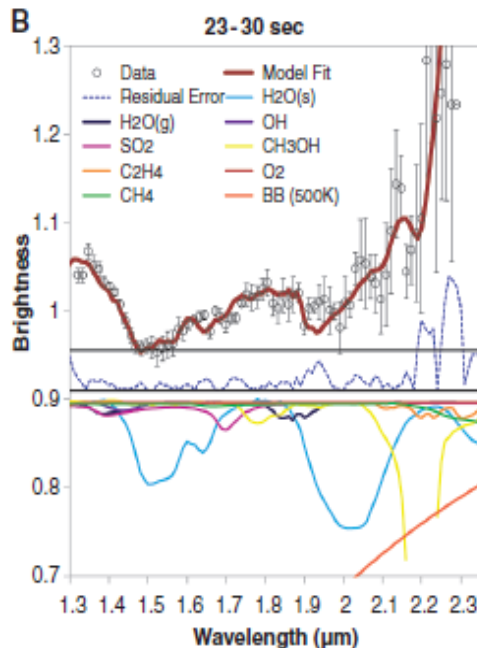
Compound	Molecules cm^{-2}	% Relative to $H_2O(g)$*
H_2O	5.1(1.4)E19	100.00%
H_2S	8.5(0.9)E18	16.75%
NH_3	3.1(1.5)E18	6.03%
SO_2	1.6(0.4)E18	3.19%
C_2H_4	1.6(1.7)E18	3.12%
CO_2	1.1(1.0)E18	2.17%
CH_3OH	7.8(42)E17	1.55%
CH_4	3.3(3.0)E17	0.65%
OH	1.7(0.4)E16	0.03%

*Abundance as described in text for fit in Fig. 3C.

Ref: "Detection of Water in the LCROSS Plume Ejecta," Colprete, et. al., Science, 22 Oct. 2010
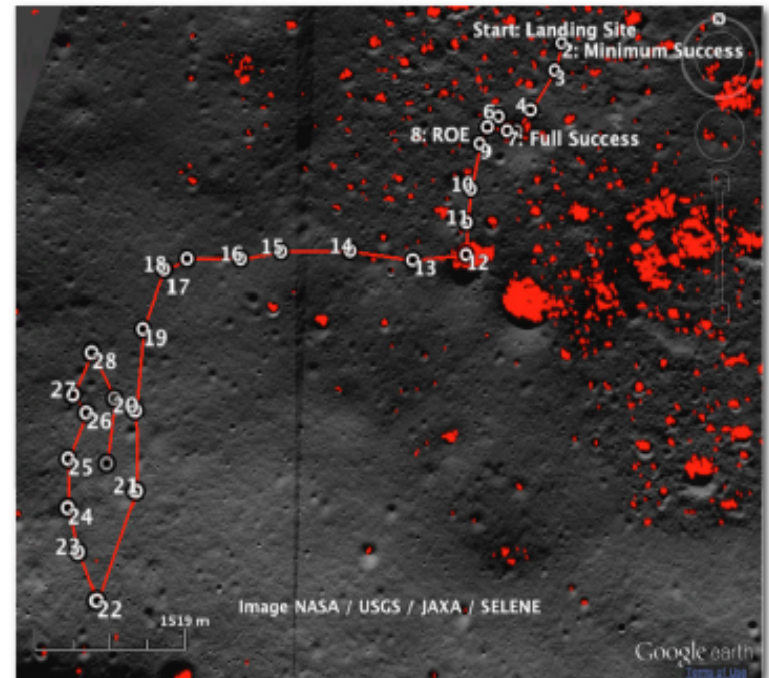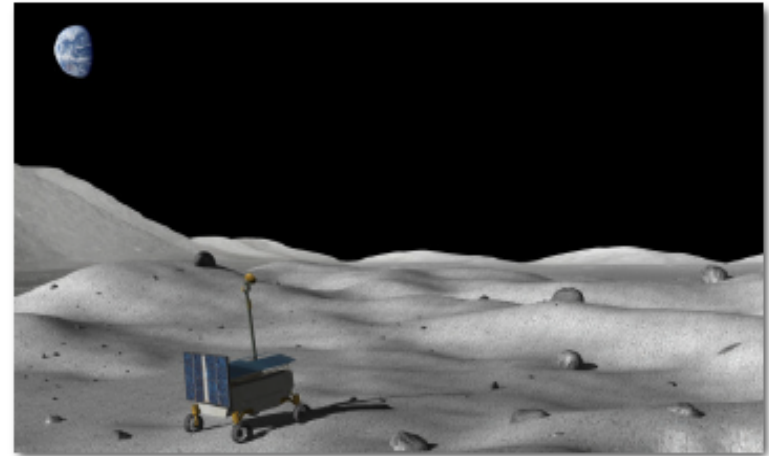
Resource Prospector (RP)

Mission

- Characterize the nature and distribution of **lunar polar volatiles**
- Demonstrate **in-situ resource utilization**: process lunar regolith

Key Points

- NASA HEOMD (AES program)
- Class D / Category 3 Mission
- Launch: 2020 (Falcon 9 v1.1)
- Duration: 6-14 Earth days
- Direct-to-Earth communications

Rover

- Mass: 300 kg (including payload)
- Dimensions: 1.4m x 1.4m x 2m
- Speed made good: 0.5 cm/s
- Power: 300W (solar powered)

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Image NASA / USGS / JAXA / SELENE
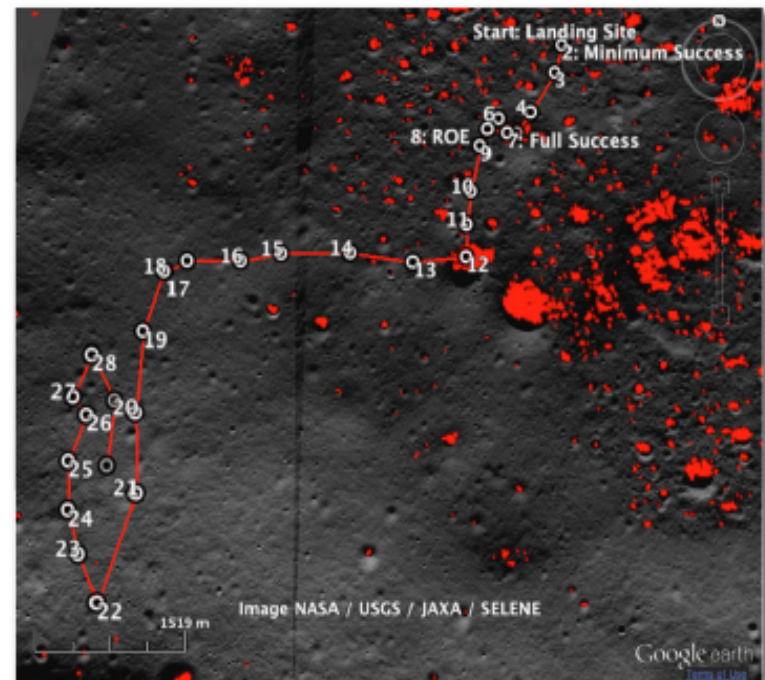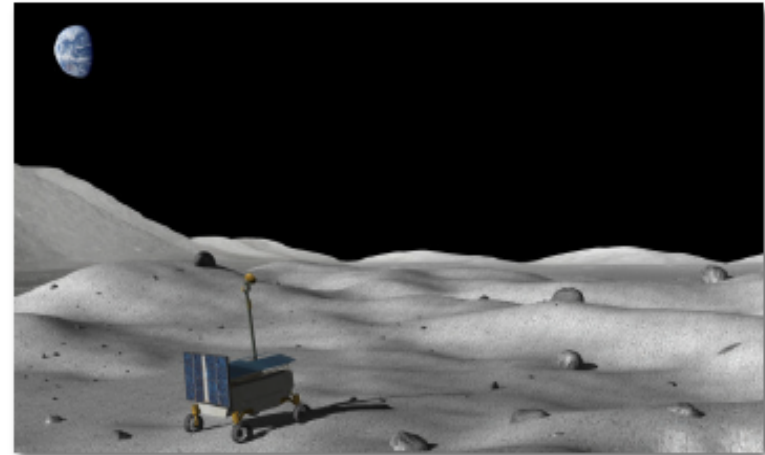
RP rover and payload during RP-15 operational testing at the JSC rock yard

Questions?